Observation of *ZZ* Production at DØ

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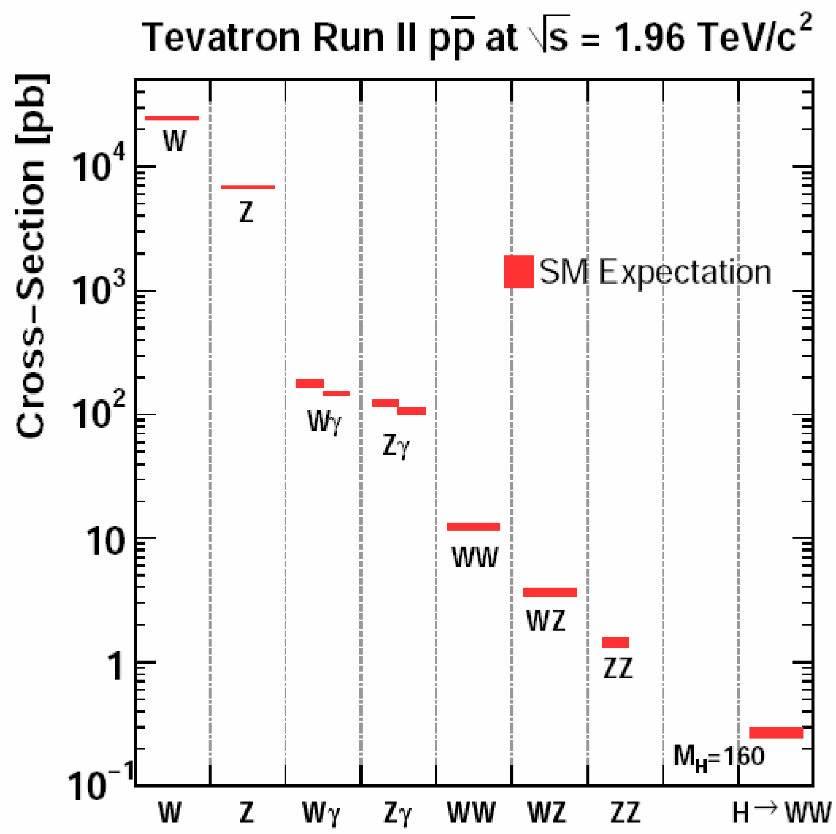
For the DØ Collaboration

Fermilab Joint Experimental-Theoretical Seminar

Diboson Physics at the Tevatron

- Measure production cross sections
- Probe gauge boson self-interactions
  - Consequence of non-Abelian nature of $SU(2)_L \otimes U(1)_Y$
  - One of the least tested areas of the SM
- Sensitive to new physics in trilinear gauge couplings (TGC)
  - Different combinations of couplings
  - Evidenced by increase in measured cross section relative to Standard Model
- Probe for new heavy resonances decaying into dibosons
- Backgrounds to numerous channels:
  - Higgs; SUSY; ttbar



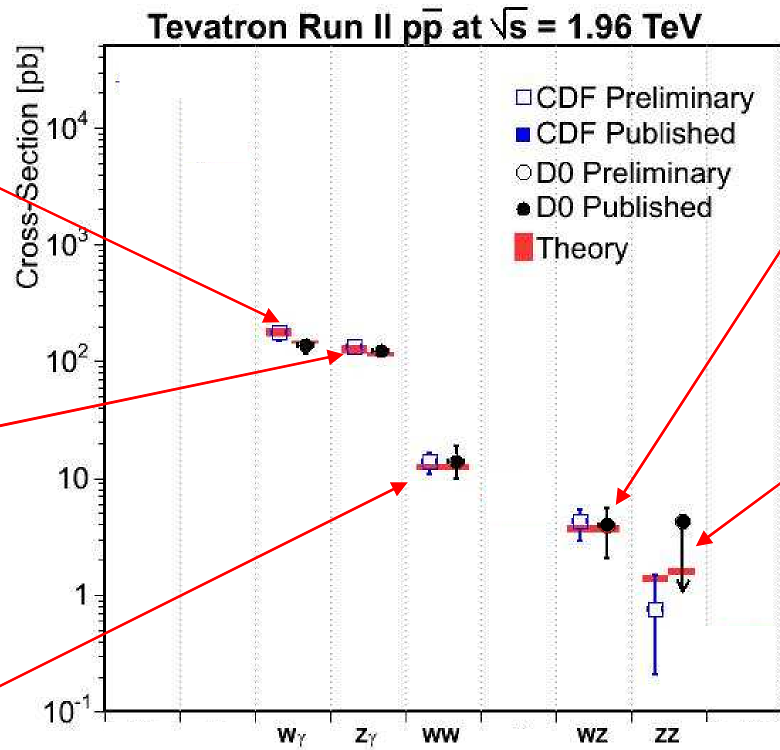
note: this is σ, not $\sigma \times$ BR

Previous DØ Diboson Results

Wγ
Preliminary cross section
Indication of radiation amplitude zero
PRD 71, 091108 (2005)
PRL 100, 241805 (2008)

Zγ
Cross section measured
Limits on ZZγ and Zγγ couplings
PLB 653, 378 (2007)

WW
Cross section measured
PRL 94, 151801 (2005)



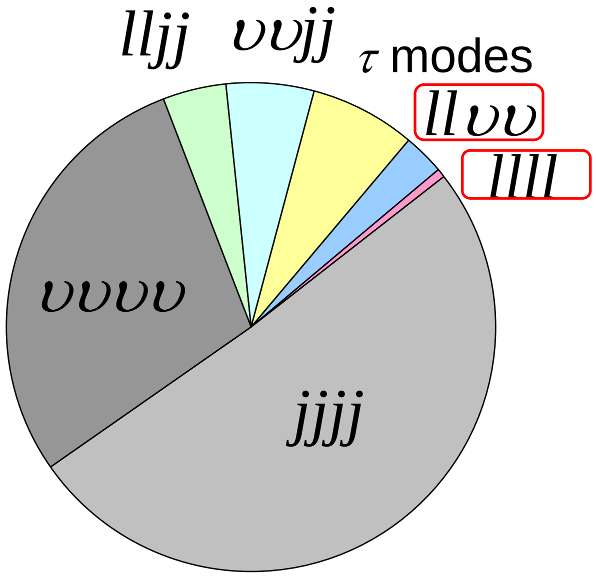
WZ
First evidence
Limits on WWZ couplings
PRD 76, 111104(R) (2007)

ZZ
Cross section limit
Limits on ZZZ and ZZγ*
couplings
PRL 100, 131801 (2008)

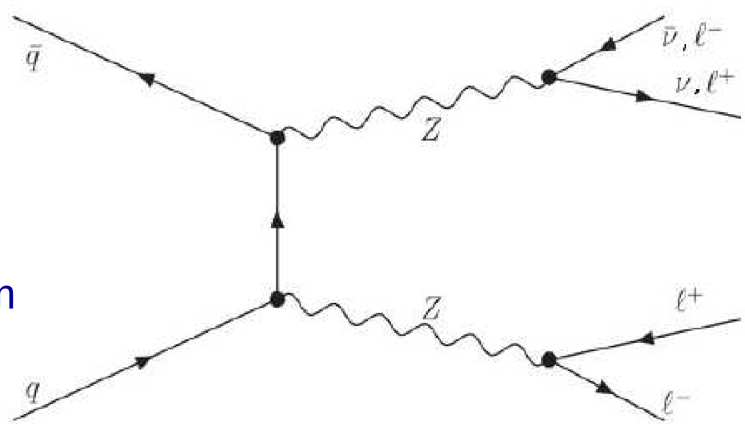
ZZ Production

- Very small production cross section
  - $\sigma^{NLO}(ZZ) = 1.4 \pm 0.1$ pb

    [J.M. Campbell and R.K. Ellis PRD 60, 113006 (1999)]
    - sqrt(s): 2.0→1.96 GeV
    - $\alpha = 1 / 128.89$
    - $\sin^2(\theta_w) = 0.2312$
    - PDFs to CTEQ6.6M

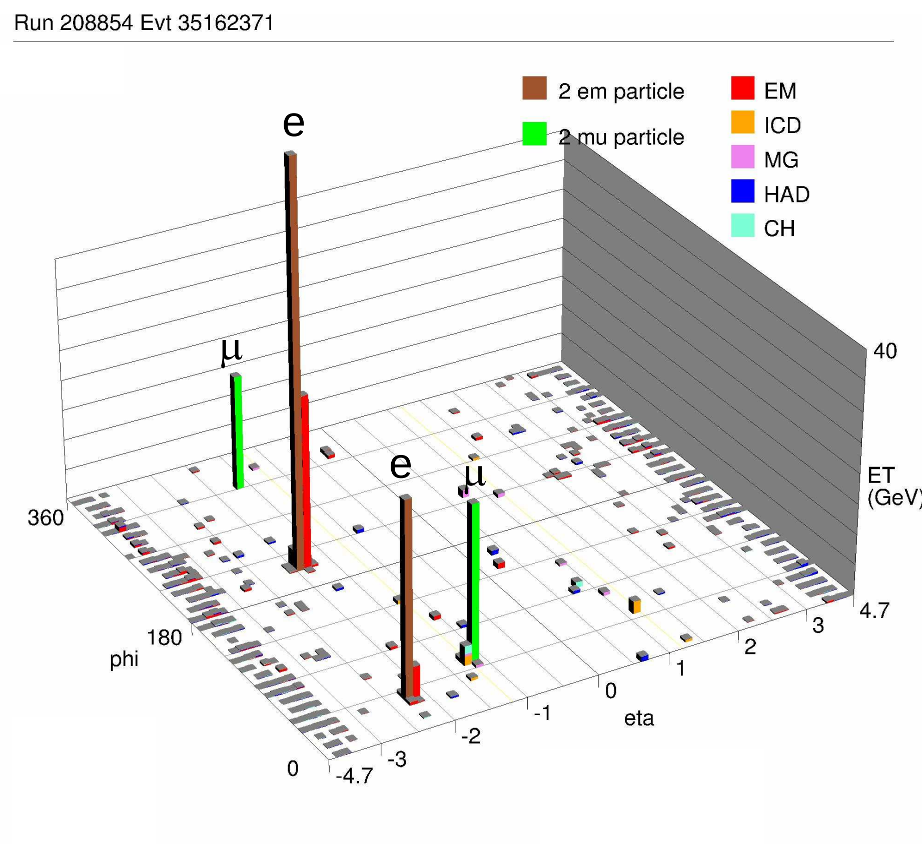


- Two main decay modes studied:
  - $ZZ \to ll\nu\nu$, with l = e or μ
    - Several significant background processes: WW, Z+jets, WZ, Drell-Yan production
    - BR = 2 x 0.2 x (2 x 0.033) = 0.026
    - Use multivariate likelihood approach to discriminate between signal and background
  - $ZZ \to llll$, with l = e or μ
    - Very clean: low background contamination from Z/γ+jets and ttbar processes
    - 6 times smaller BR = $(2 \times 0.033)^2 = 0.0044$
    - Look directly for four lepton signature



First DØ ZZ Analysis

- Looked at 4e, 4μ and 2e2μ channels
- Required a dilepton mass cut of 30 GeV
- Observe one $ee\mu\mu$ candidate in 1 fb^{-1} of data
  - Expected background of 0.13 ± 0.03 vents
  - SM predicts 1.71 ± 0.15 events
    - M(ee) = 93.4 GeV
    - M($\mu\mu$) = 33.4 GeV
- Set upper limit of $\sigma(ZZ/Z\gamma^*)$ < 4.4 pb at 95% CL
- Set Limits on Anomalous Couplings

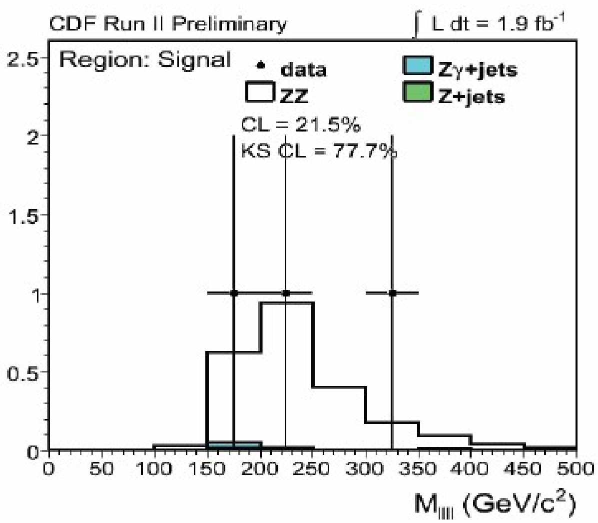


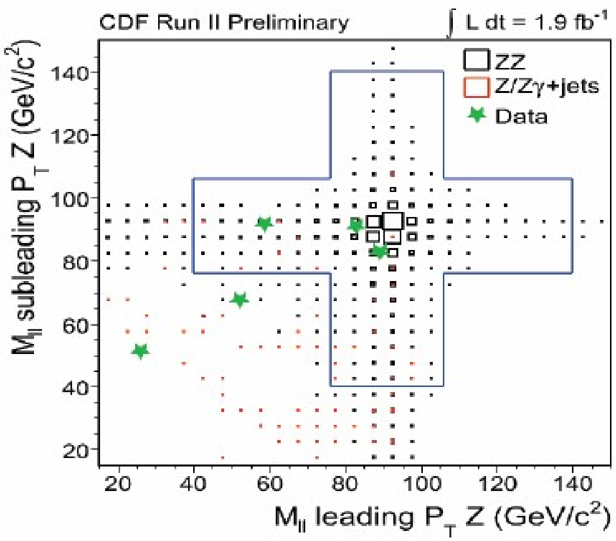
PRL 100, 131801 (2008)

CDF $ZZ \rightarrow llll$

- Split 4e, 4μ and 2e2μ into 7 exclusive categories depending whether a lepton has a track and/or is identified explicitly
- One pair of leptons with M(*ll*) in [76 – 106] GeV; the other pair with M(*ll*) in [40 – 140] GeV

1 fb^{-1} Category	Candidates without a a trackless electron	Candidates with a a trackless electron
ZZ	$1.990 \pm 0.013 \pm 0.210$	$0.278 \pm 0.005 \pm 0.029$
Z+jets/$Z\gamma$+jets	$0.014^{+0.010}_{-0.007} \pm 0.003$	$0.082^{+0.089}_{-0.060} \pm 0.016$
Total	$2.004^{+0.016}_{-0.015} \pm 0.210$	$0.360^{+0.089}_{-0.060} \pm 0.033$
Observed	2	1

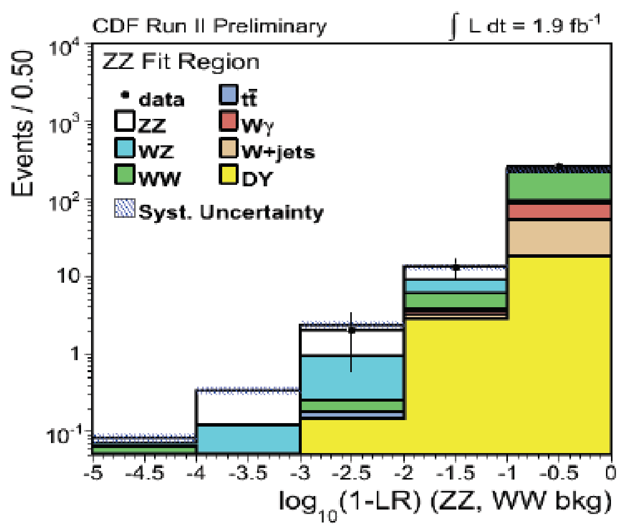




CDF $ZZ \rightarrow ll\nu\nu$ and Combination

- Select events with ee/$\mu\mu$ and large MET. Veto on central jets to suppress ttbar contribution.
  - Observe 276 events in preselected sample
  - Expect 14 ± 2 signal events
- Use full kinematic information to form a likelihood ratio

$$LR \equiv \frac{P_{ZZ}}{P_{ZZ} + P_{WW}}$$



- Combine $ZZ \rightarrow llll$ and $ZZ \rightarrow ll\nu\nu$ channels:

50% chance to observe 5σ effect

Observed Results

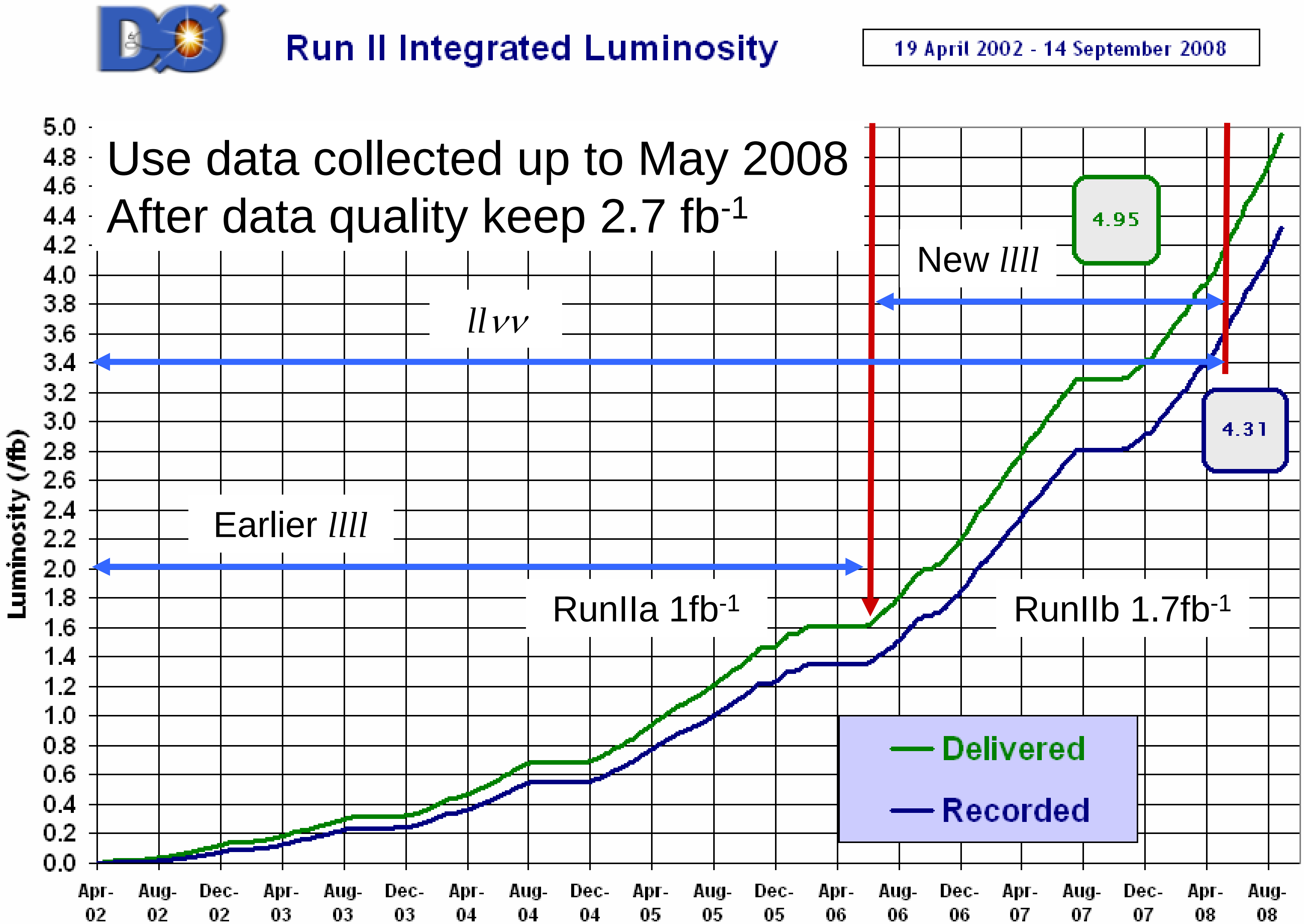
P-Value	0.12	1.1×10^{-5}	5.1×10^{-6}
Significance	1.2 σ	4.2 σ	$\boxed{4.4\ \sigma}$

- Cross section measurement:

$$\boxed{\sigma(ZZ) = 1.4^{+0.7}_{-0.6}\ \text{pb}}$$

PRL 100, 201801 (2008)

Data



Run II Integrated Luminosity
19 April 2002 - 14 September 2008
Use data collected up to May 2008
After data quality keep 2.7 fb^{-1}
New $llll$
4.95
$ll\nu\nu$
4.31
Earlier $llll$
RunIIa 1fb^{-1}
RunIIb 1.7fb^{-1}
Delivered
Recorded
Luminosity (/fb)
5.0
4.8
4.6
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Apr-02
Aug-02
Dec-02
Apr-03
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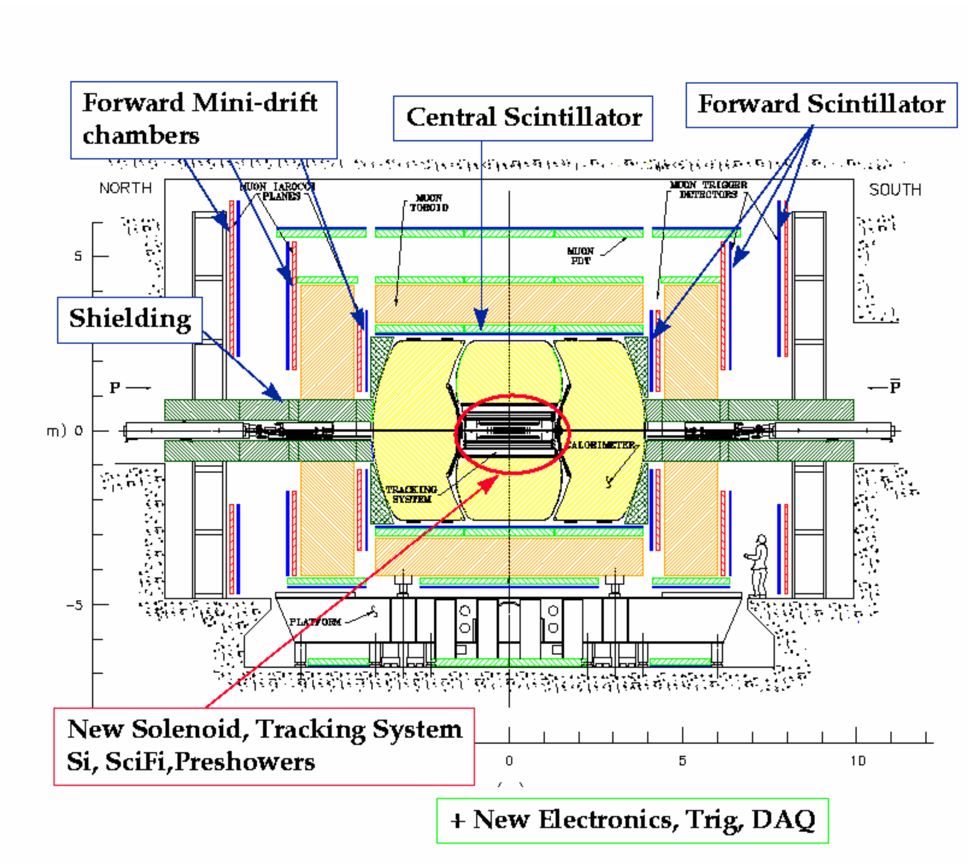
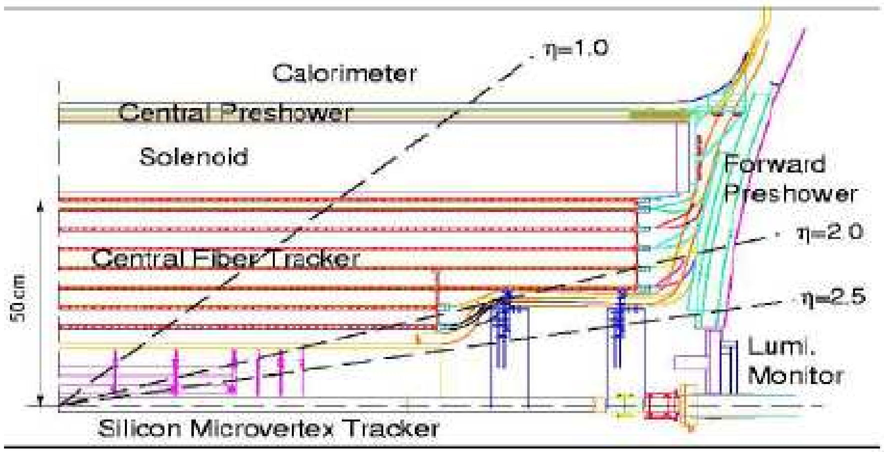




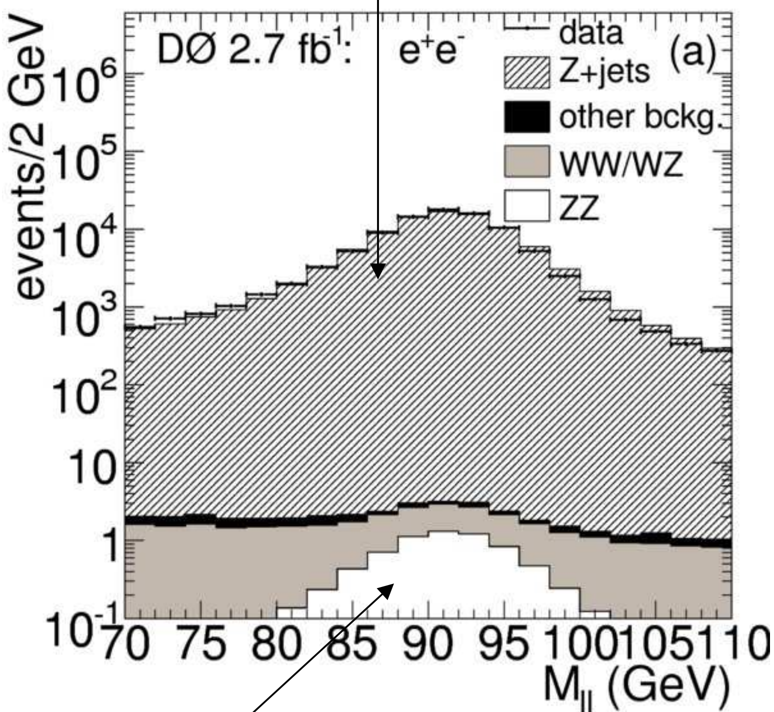
- Silicon micro-strip vertex detector
- Scintillating fiber tracker
- 2 T solenoid magnet
- Uranium Liquid Argon calorimeter
- 1.8 T toroid magnet
- Wire tracking / scintillation counter muon detector
- Pseudorapidity coverage:
  - Electrons: $|\eta| < 3.2$
  - Muons: $|\eta| < 2.0$

ZZ→$ll\nu\nu$

ZZ→$ll\nu\nu$: Electron Selection

2.7fb^{-1} : OR of single electron triggers – Normalize to the Z peak in Data

Inclusive Z background



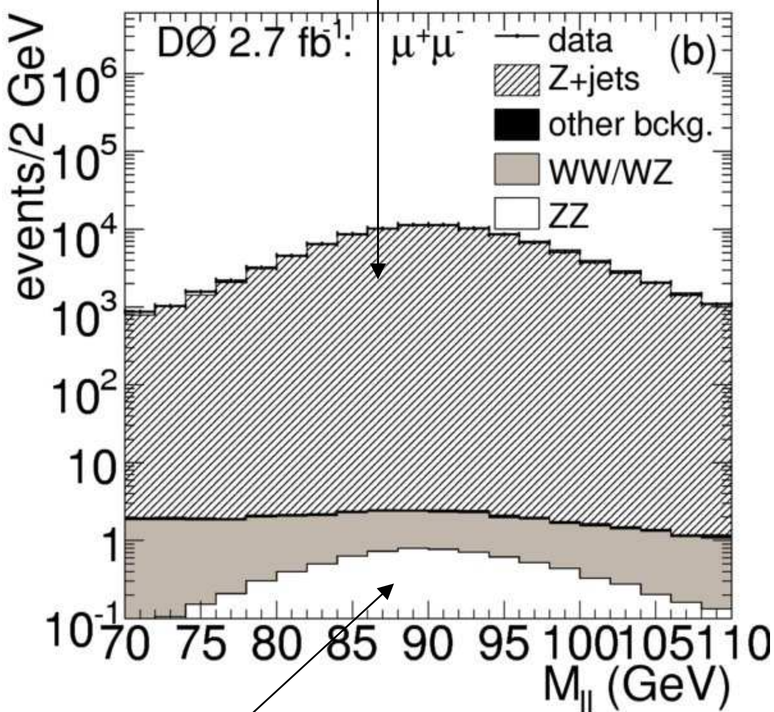
ZZ signal

- p_T > 15 GeV
- Within the central (|η| < 1.1) or forward (1.5 < |η| < 2.5) calorimeter regions
- Tight Isolation
- Tight cut on multi-variate parameter of energy and shower distribution

ZZ→$ll\nu\nu$: Muon Selection

2.7fb^{-1} : OR of single muon triggers – Normalize to the Z peak in Data

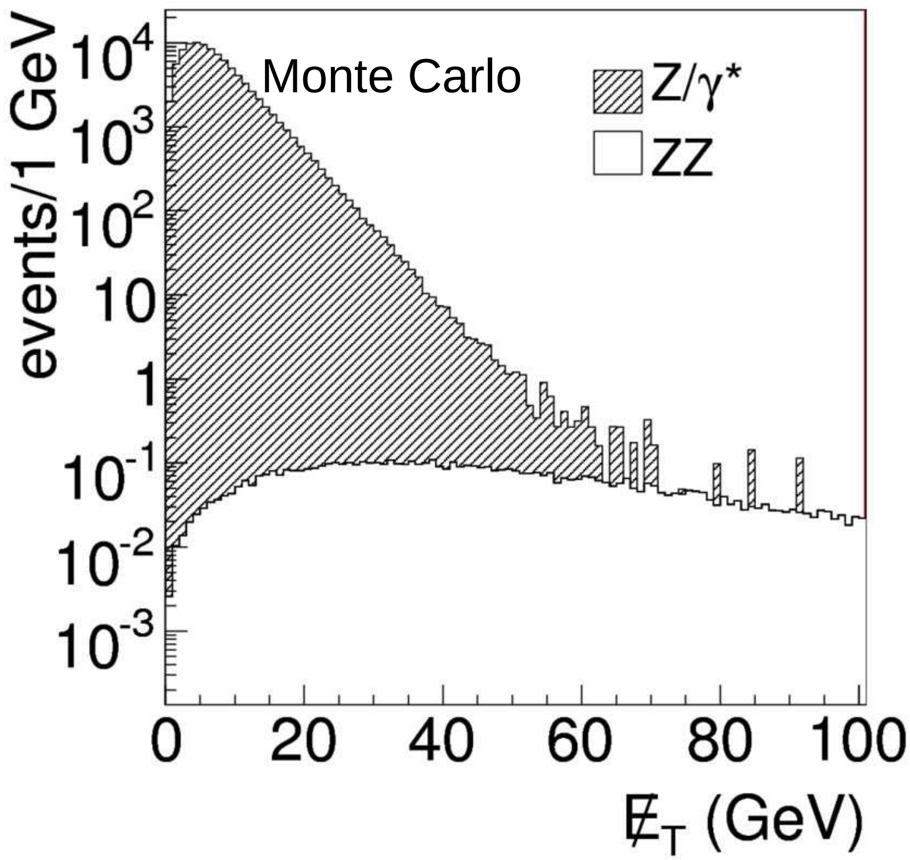
Inclusive Z background



ZZ signal

- p_T > 15 GeV
- Central track match with:
  - at least 1 hit in the Silicon Microstrip Tracker (SMT)
  - A distance of closest approach < 0.02 cm
- Tight calorimeter isolation

ZZ→$ll\nu\nu$: Event Selection

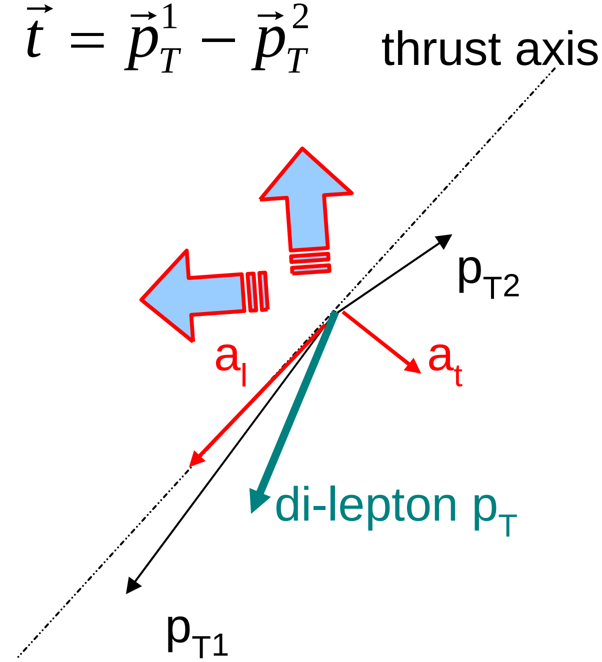


- Reject events with low p_T or poorly reconstructed electrons, muons, taus and isolated tracks
- Require # of jets <= 2 w/ p_T > 15 GeV
- Require Di-lepton Invariant Mass 70 < M_{ll} < 110 GeV
- Need to filter against Z/γ* events with no expected large MET
  - MET alone is not a sufficient discriminator due to the difficulties of measuring it in a detector

ZZ→$ll\nu\nu$: Motivating METPrime

- To reduce the contribution of fake MET no direct cut on MET → build a variable sensitive to "true MET"
- decompose di-lepton p_T in 2 components with respect to thrust axis:
  - a_l: sensitive to p_T mismeasurement
  - a_t: sensitive to recoil activity mismeasurment
- build a variable which gives more weight to a_t (add in quadrature with different weights) → $\hat{\not{E}}'_T$
- balance against activity in the opposite hemisphere and conservatively reduce using the corresponding uncertainties

$$\vec{t} = \vec{p}_T^{\,1} - \vec{p}_T^{\,2}$$

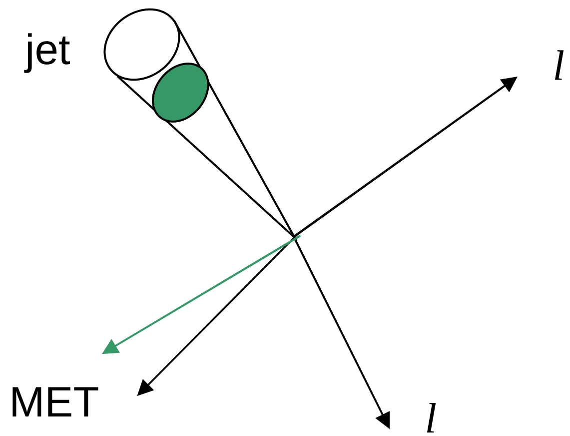


By construction, all uncertainties and misreconstruction can ONLY reduce the value of $\hat{\not{E}}'_T$

ZZ→$llνν$: METPrime Reductions

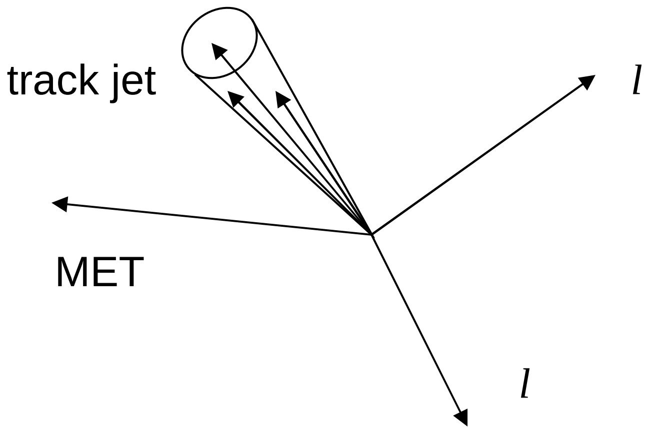
- Calorimeter Recoil Activity
  - based on the vector sum of jet E_T or the uncorrected missing transverse energy, picking the one with the largest magnitude
  - A jet is only included in the sum if it's p_T is in the direction opposite the dilepton pair

$$\delta a_t^{cal} = 2 \times \min(\Sigma \vec{p_T}^{jets} \cdot \hat{a}_t, -\vec{\not{E}_T} \cdot \hat{a}_t, 0)$$
$$\delta a_l^{cal} = 2 \times \min(\Sigma \vec{p_T}^{jets} \cdot \hat{a}_l, -\vec{\not{E}_T} \cdot \hat{a}_l, 0)$$



ZZ→$ll\nu\nu$: METPrime Reductions

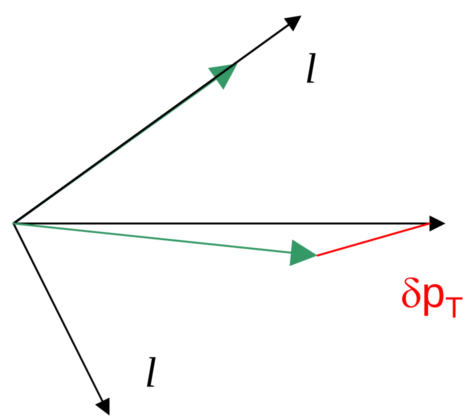
- Recoiling Tracks
  - Account for tracks which are well separated from the candidate leptons and calorimeter jets
    - Form jets of tracks with cone size 0.5:
    - Accounts for events in which the recoil activity is not observed in the calorimeter as jets.
    - Trackjets as well are only included in the sum if their pT is in the direction opposite the dilepton pair



$$\delta a_t^{trk} = (\Sigma \vec{p}_T^{\,tjet}) \cdot \hat{a}_t$$
$$\delta a_l^{trk} = (\Sigma \vec{p}_T^{\,tjet}) \cdot \hat{a}_l$$

ZZ→$llvv$: METPrime Reductions

- Lepton p_T Uncertainty
  - accounting for lepton transverse momentum measurement uncertainties
  - Fluctuate the lepton p_T by one standard deviation, minimizing the projections of the dilepton



$$\vec{p}_T' = (1-\sigma)\,\vec{p}_T$$

$$a_t^{\ell\ell'} = \vec{p}_T^{\,\ell\ell'} \cdot \hat{a}_t{}'$$

$$\delta a_t^{\ell\ell} = a_t^{\ell\ell'} - a_t^{\ell\ell}$$

$$\delta a_l^{\ell\ell} = \left(-\sigma_1 \vec{p}_T^{\,(1)} + \sigma_2 \vec{p}_T^{\,(2)}\right) \cdot \hat{a}_l$$

ZZ→$ll\nu\nu$: METPrime Construction

- Components are computed with optimized factors k and k' determined by applying a loose cut on METPrime and maximizing signal over background

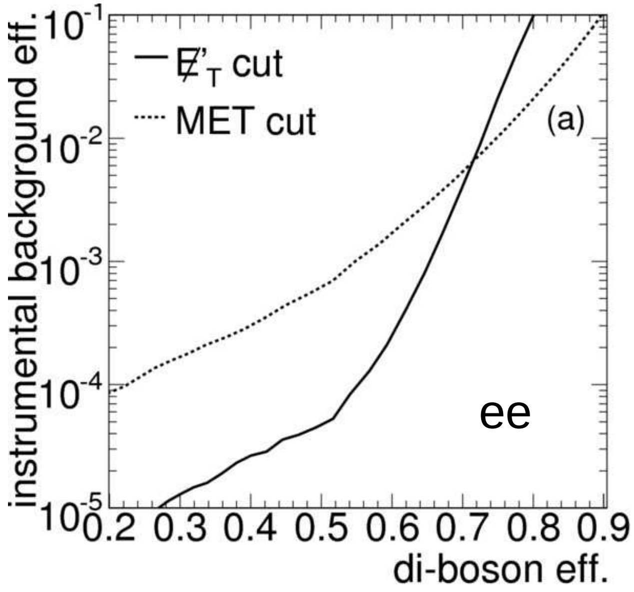
$$
\begin{aligned}
a_t &= a_t^{\ell\ell} + \delta a_t^{cal} + k' \times \delta a_t^{trk} + k \times \delta a_t^{\ell\ell} \\
a_l &= a_l^{\ell\ell} + \delta a_l^{cal} + k' \times \delta a_l^{trk} + k \times \delta a_l^{\ell\ell}
\end{aligned}
$$

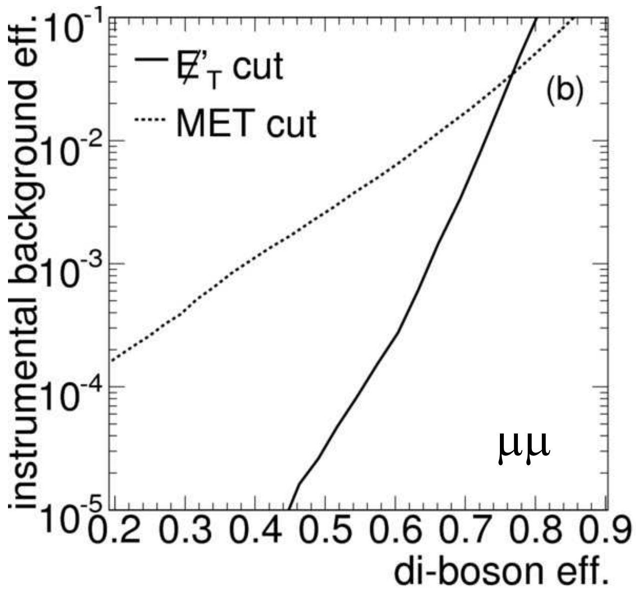
- If there is no significant missing transverse momentum in a particular direction (component is < 0), the component is ignored

$$
\begin{aligned}
a'_t &= \max(a_t, 0) \\
a'_l &= \max(a_l, 0)
\end{aligned}
$$

- Final METPrime is: $\not{E}'_T = \sqrt{a_l'^2 + (1.5a'_t)^2}$

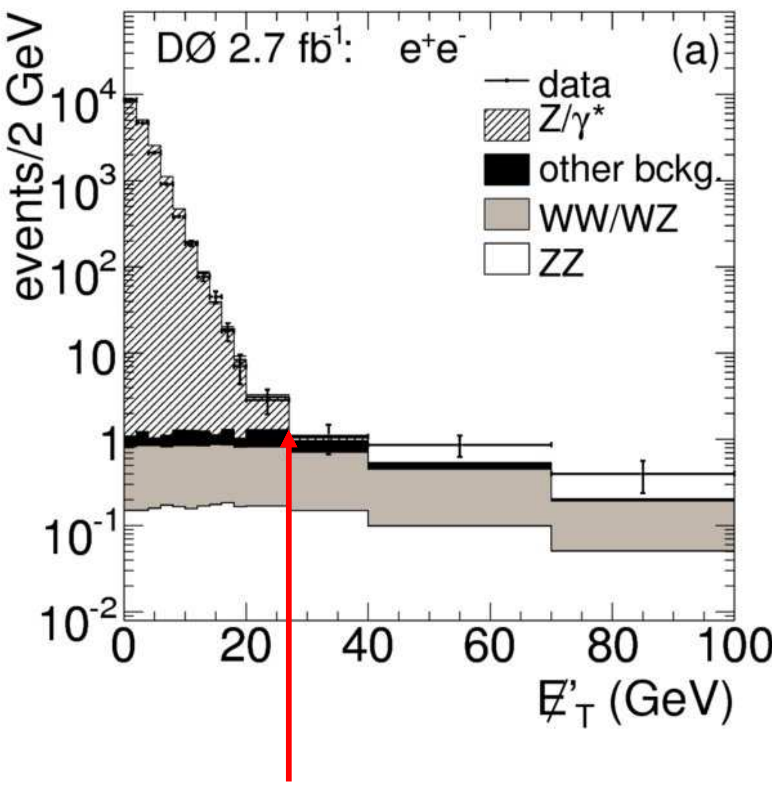
ZZ→$ll\nu\nu$: METPrime Performance





- The efficiency of WW, WZ, and ZZ events vs Inclusive Z events using MET and METPrime
  - Signal efficiency
    - 0.45 for ee
    - 0.36 for $\mu\mu$
- See over an order of magnitude better rejection using METPrime

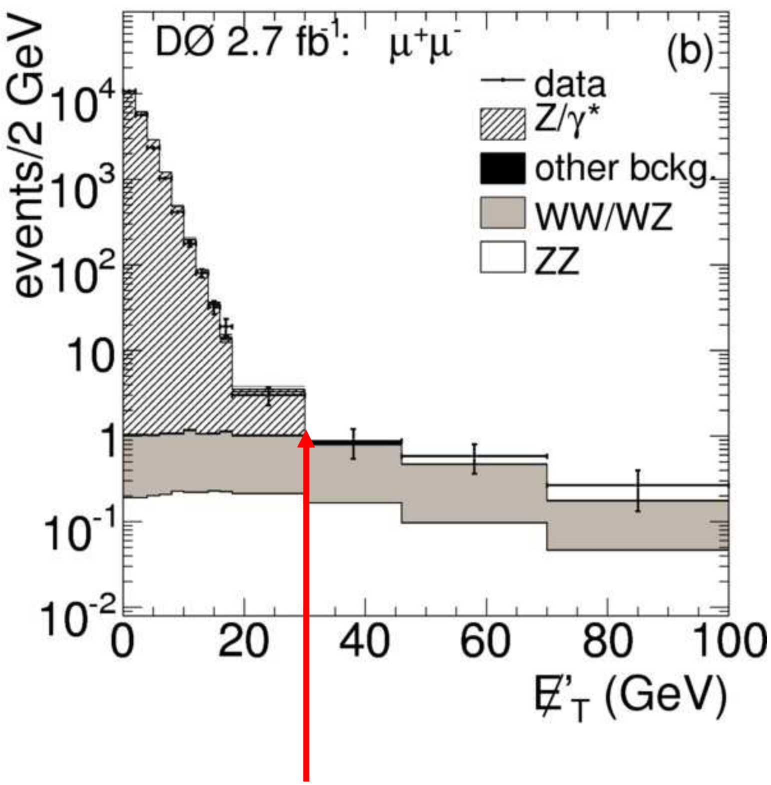
ZZ→$ll\nu\nu$: ee Results



METPrime Cut

Sample	dilepton selection	$\not{E}'_T$ requirement
$Z \to \ell^+\ell^-$	$\boxed{1.18 \times 10^5}$	0.5 ± 0.2
$Z \to \tau^+\tau^-$	48.3	0.35
W+Jets	18.2	2.7 ± 0.4
$t\bar{t}$	16.4	0.34
WW	28.0	$\boxed{10.6 \pm 0.1}$
WZ	19.2	1.08
$W\gamma$	2.0	0.01
Predicted Background	1.19×10^5	15.6 ± 0.4
$ZZ \to \ell^+\ell^-\ell'^+\ell'^-$	2.9	0.02
$ZZ \to \ell^+\ell^-\nu\bar{\nu}$	8.9	4.03
Predicted Total	1.19×10^5	19.6 ± 0.4
Data	118,850	28

ZZ→*ll*νν: μμ Results



METPrime Cut

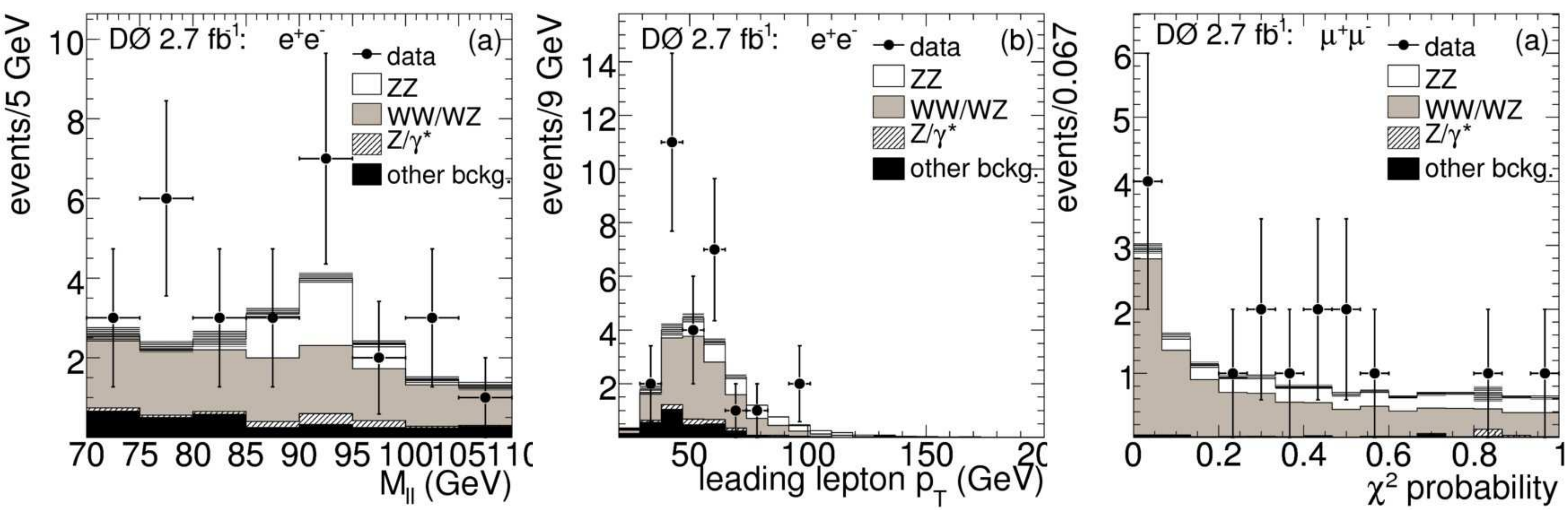
Sample	dilepton selection	$\not{E}'_T$ requirement
$Z \to \ell^+\ell^-$	$\boxed{1.30 \times 10^5}$	0.1 ± 0.1
$Z \to \tau^+\tau^-$	53.3	0.09
W+Jets	–	< 0.01
$t\bar{t}$	16.0	0.21
WW	32.0	$\boxed{9.7 \pm 0.1}$
WZ	18.3	0.82
Predicted Background	1.30×10^5	10.9 ± 0.3
$ZZ \to \ell^+\ell^-\ell'^+\ell'^-$	2.89	0.00
$ZZ \to \ell^+\ell^-\nu\bar{\nu}$	9.48	3.39
Predicted Total	1.30×10^5	14.3 ± 0.3
Data	127,960	15

ZZ→$ll\nu\nu$: Likelihood Input

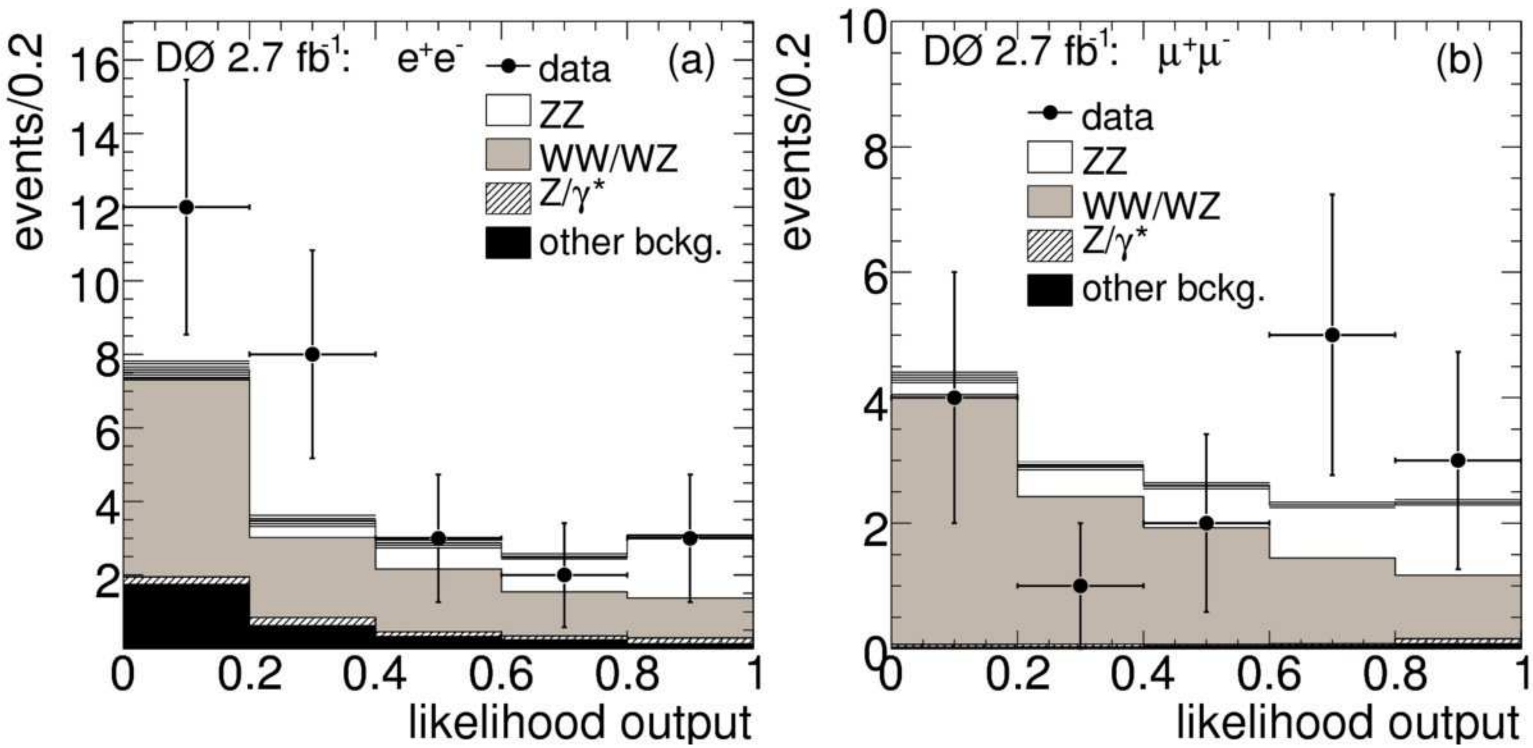
The ZZ signal is extracted from the remaining backgrounds using a likelihood

Likelihood Variables:

- Di-lepton mass (ee)
- Chi2 kinematic fit ($\mu\mu$)
- Leading lepton p_T
- $\Delta\Phi$(lead lep, di-lep)
- cos(θ*)



ZZ→$ll\nu\nu$: Likelihood Output



$ZZ \to ll\nu\nu$: Systematics

- Uncertainties dominated by the following: ee ($\mu\mu$)
  - 16% (-) Normalization of W+jets background
  - 18% (3%) Number of Z events surviving METPrime cut
    - Influenced by small MC stats in region of cut
    - ee is more sparse than $\mu\mu$, hence the difference
      - $\rightarrow$Systematic assigned to 0.5 (0.1) predicted events, so impact on analysis is limited

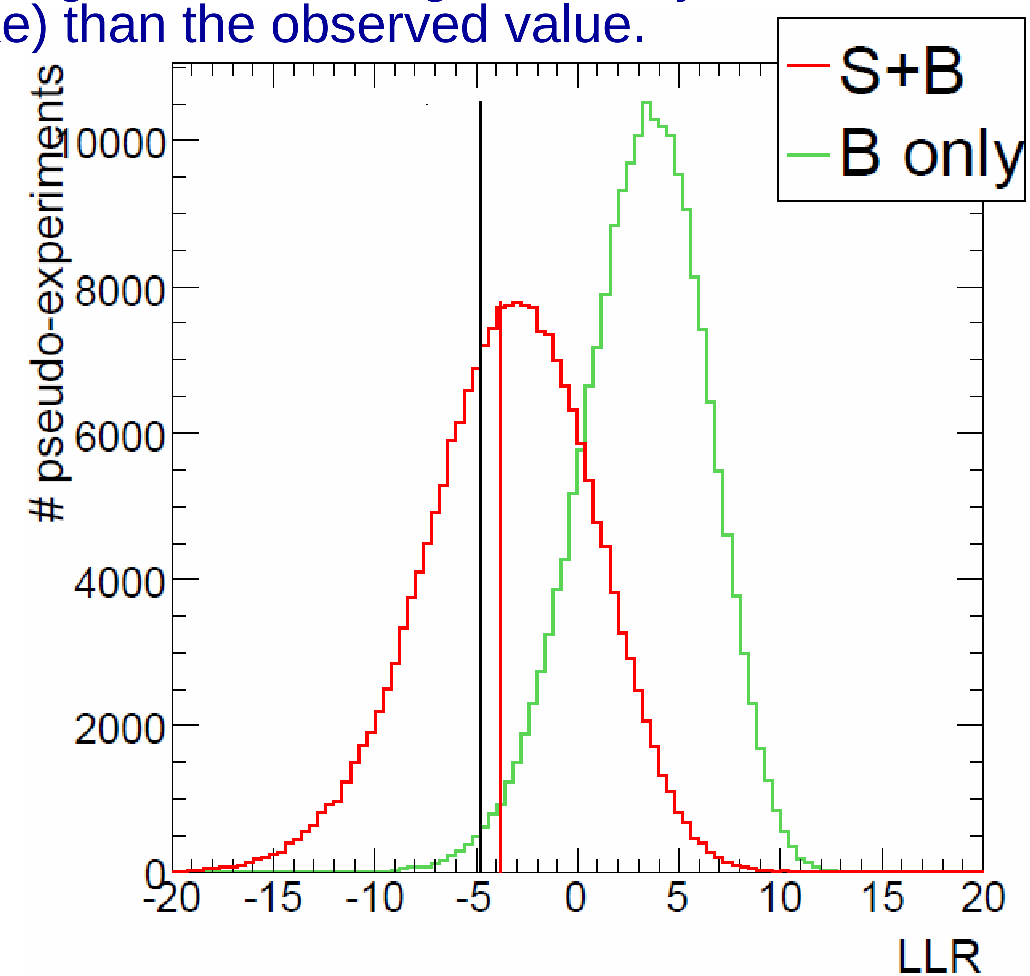
ZZ→$llvv$: Significance

- Performed using a semi-frequentist approach
  - Assume data is drawn randomly from a Poisson parent distribution
- Input is the information in channels (binned)
  - s is expected signal, b is expected background, d is data
  - Generate pseudo-experiments via random Poisson with mean value from expected b and s+b
  - Systematic uncertainties treated using a Bayesian model
    - Treated as Gaussian-distributed, randomly sampled for each pseudo-experiment
    - Nominal background prediction varied according to smeared values of systematics, changing the mean of the random Poisson with each pseudo-experiment
- Use a negative log-likelihood ratio (LLR) test statistic:

$$LLR(\vec{s},\vec{b},\vec{d}) = \sum_{i=0}^{N_{bins}} s_i - d_i \ln(1+\frac{s_i}{b_i})$$

ZZ→$ll\nu\nu$: Significance (cont'd)

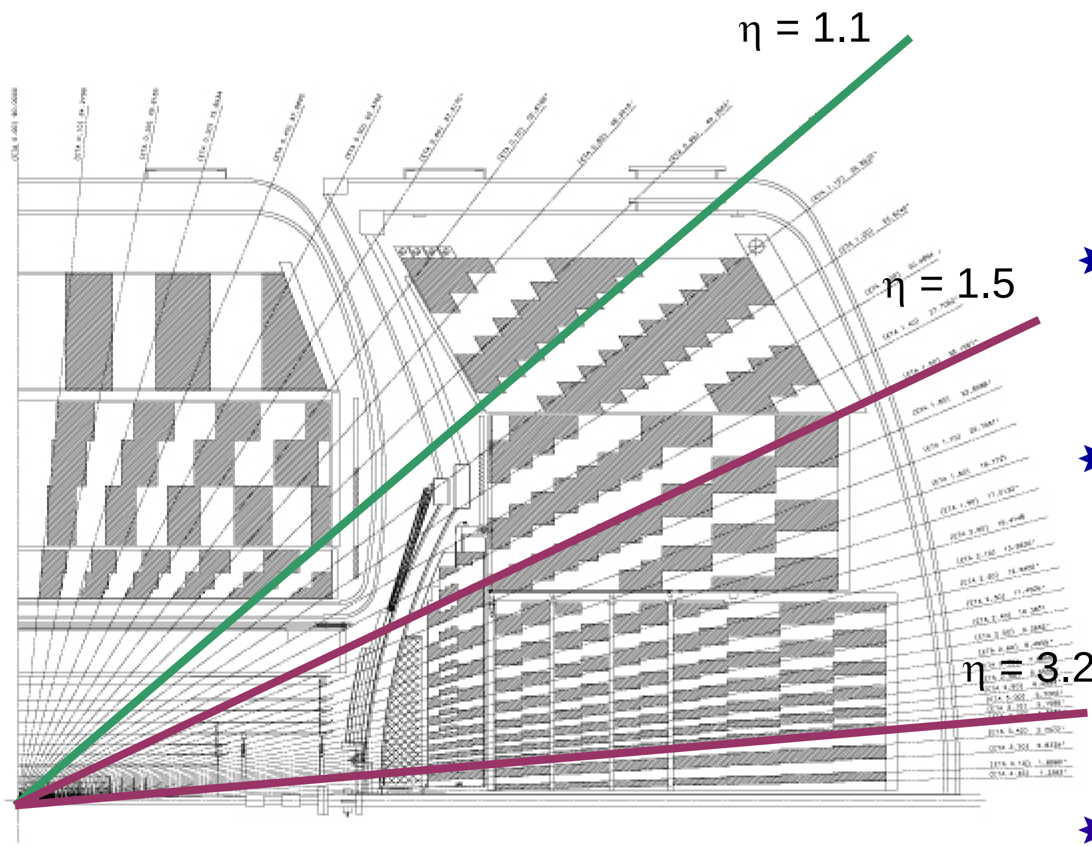
- LLR is linear in bins: makes channel addition trivial
- Implicitly imports info on the shapes of parent distributions
- The probability that background-only hypothesis can fluctuate up to the observed yield, "p-value", is the integral of the background-only LLR distribution below (more signal like) than the observed value.



- Get a p-value of 0.0042
  - 2.6σ (2.0σ expected)
- Accepted by PRD arXiv:0808.0269 [hep-ex] (2008)

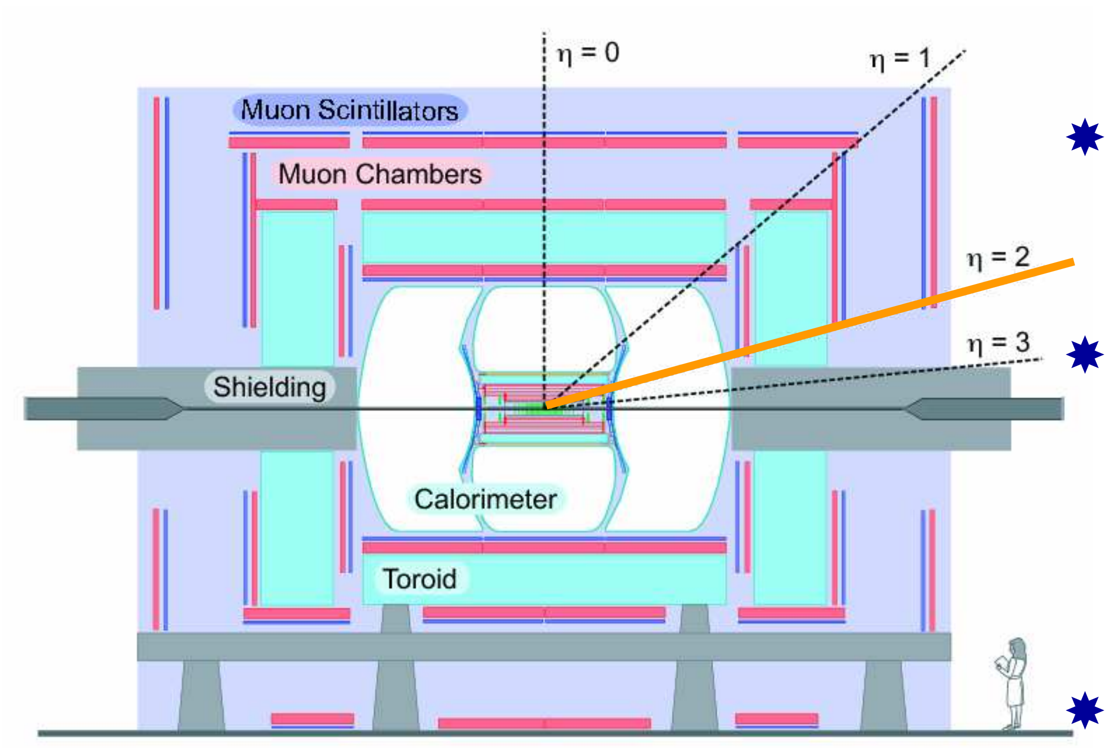
$ZZ \rightarrow llll$

$ZZ \rightarrow llll$: Electron Selection



- Must be reconstructed either in the central $|\eta| < 1.1$ or forward $1.5 < |\eta| < 3.2$ EM calorimeter
- Must be isolated from other energy clusters
- Central electrons must be matched to a track and satisfy a cut on multi-variate parameter of energy and shower distribution
- Forward electrons not required to have track, but must satisfy more stringent shape requirements

ZZ→*llll*: Muon Selection

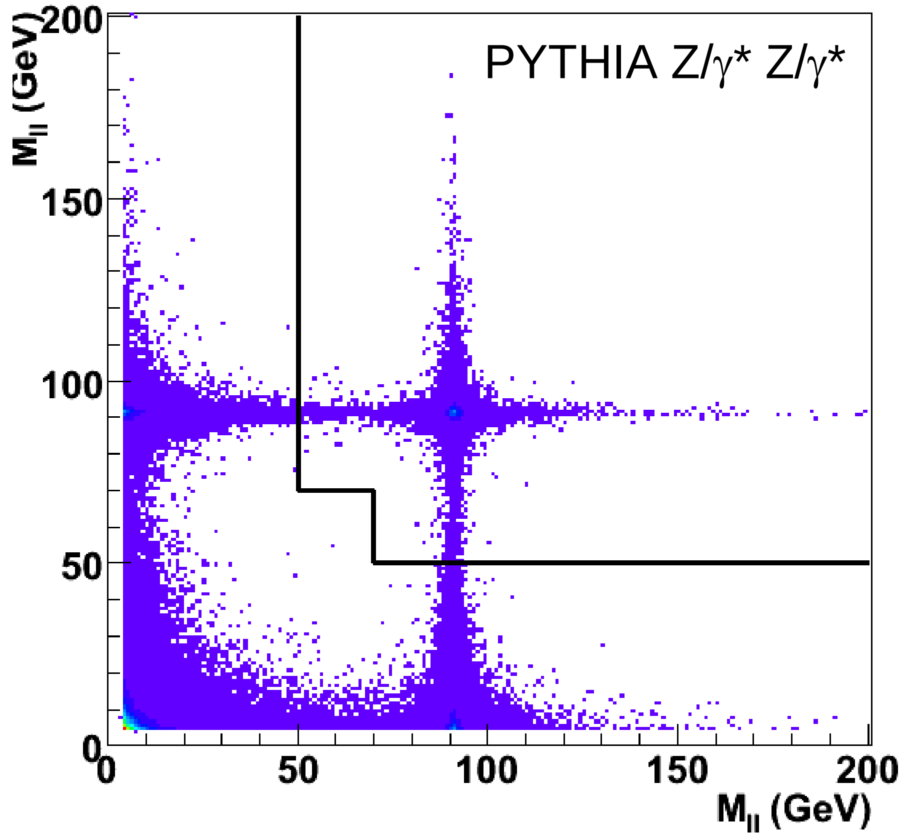


- Must be matched to a central track
- Must satisfy timing requirements in the muon detector
- Track must satisfy a distance of closest approach cut
  - < 0.02 cm w/ SMT hits
  - < 0.2 cm w/o SMT hits
- Must satisfy calorimeter isolation requirements if not enough hits in the muon system

ZZ→*llll*: Mass cut

- As it is impossible to differentiate between Z and γ^* quantum mechanical states experimentally, we must set a mass cut a priori at which we decide to call the observed particle a Z. This is based on Z/γ^* Z/γ^* PYTHIA Monte Carlo:

- $M(Z_1) > 70$ GeV,
  $M(Z_2) > 50$ GeV

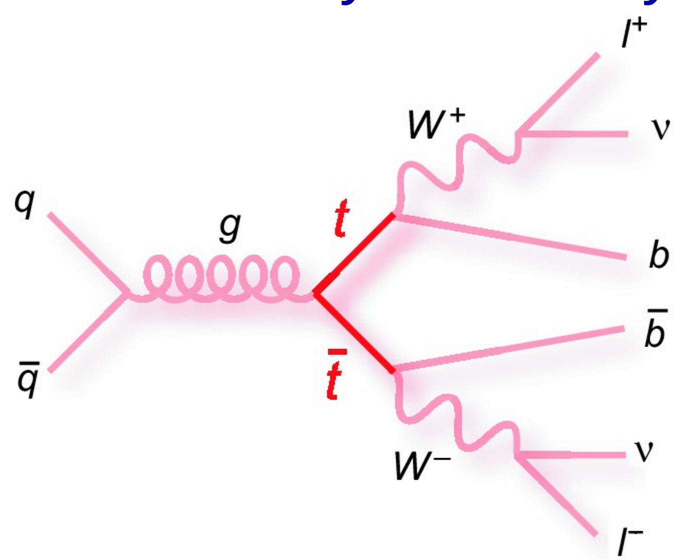


ZZ→*llll*: Event Selection

- Common Requirements
  - Require passage of OR of single and di-lepton triggers
  - Require 4 well reconstructed leptons
    - $p_{T1} > 30$ GeV, $p_{T2} > 25$ GeV, $p_{T3} > 15$ GeV, $p_{T4} > 15$ GeV
  - $M_1(ll) > 70$ GeV, $M_2(ll) > 50$ GeV
- 4e
  - Break into subchannels of 2, 3 or 4 central electrons
    - QCD background expected to decrease based on number of track matched electrons
- 4μ
  - Require at least three calorimeter isolated muons to reduce ttbar background
  - Cosine of angle between all pairs < 0.96 to reduce misreconstruction
  - Require tracks to originate from primary vertex
- 2e2μ
  - Require passage of common triggers OR electron-muon triggers
  - Require two well reconstructed electrons and muons
    - $p_{T1} > 25$ GeV, $p_{T2} > 15$ GeV in both cases
  - Break into subchannels of 0, 1 or 2 central electrons
  - Require isolation (for at least one muon), angle and track requirement as muons
  - $\Delta R > 0.2$ between electrons and muons to remove inclusive $Z\to\mu\mu$ events where muons radiate a photon

ZZ→*llll*: Expectation

- Use PYTHIA Monte Carlo passed through GEANT simulation
  - Normalize to luminosity using mass cut on MC truth mass of the Z bosons
- Apply appropriate cut flow
- For signal expectation, also include small contribution from case where Z decays to τ pair which then decays to satisfy cut flow requirement
- For ttbar background, use a sample of ttbar→2b+2*l*+2ν

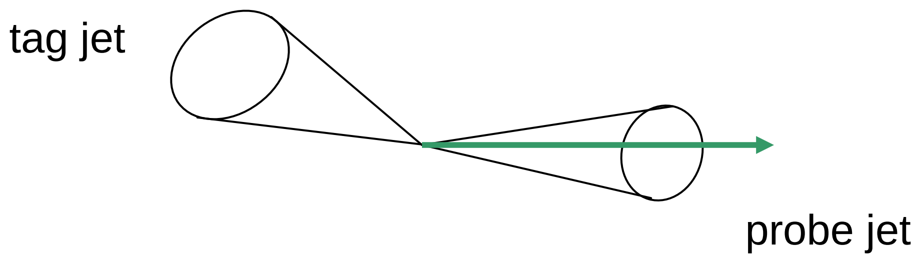


- End with acceptance x efficiency which is used to extract the expected yield

$ZZ \rightarrow \mathit{llll}$: Lepton Misidentification

- Calculate lepton misidentification rate of jets using tag and probe method from data
  - Require two jets, one of which must pass tight requirements (tag) and the other (probe) is in the opposite direction
  - Look for good leptons in the event that are near the probe jet

Require some energy in EM calorimeter, energy in the hadronic calorimeter not caused by “hot” cells in detector



  - Ratio of events where probe jet is associated to a lepton to all probe jets is the misidentification rate
    - For electrons, this is parameterized in terms of η and p_T and is on the order of 4×10^{-4} for central jets and 5×10^{-3} for forward jets
    - For muons, this is parameterized in terms of tag jet p_T and probe jet η for different muon pT and isolation. For jets of p_T = 15 (100) GeV that aren’t isolated is on the order of 10^{-4} (10^{-2}) and if isolated 10^{-5} (10^{-4})

ZZ→*llll*: QCD Background

- Misidentification rate is then applied to data requiring jets in the final state

- For 4e look at 3e+jet, for 2e2μ look at 2μ+e+jet and 2e+2jets final states to account for contributions from Z+γ+jets where the γ has been converted to an electron, plus Z/W/WZ/WW+jet contributions
  - This method double counts the contribution from Z+jets, so is corrected by finding the contribution from 2e+2jet and 2μ+2jet final states. This correction is O(20%).

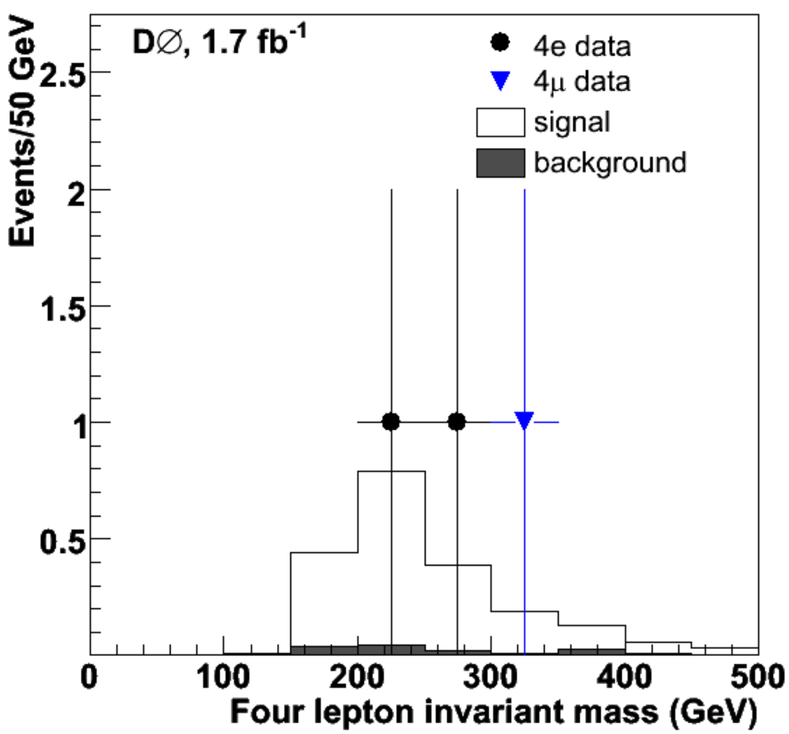
- For the 4μ channel, just use 2μ+2jet final state, but no mass cut is applied since the kinematics between muons and jets is different

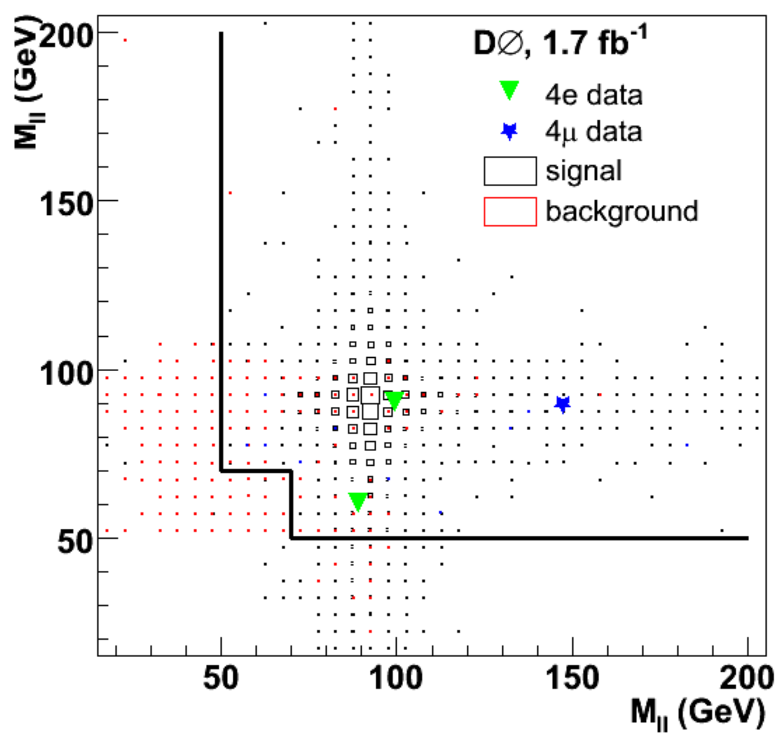
$ZZ \rightarrow llll$: Systematics

- Systematics are dominated by the following:
  - Signal:
    - 4% (2.5%) uncertainty on lepton identification and reconstruction efficiencies for 4e,4μ (2e2μ)
    - 6.1% uncertainty in luminosity
  - ttbar:
    - 10% from uncertainty in cross section and variation in cross-section and acceptance from uncertainty in top mass
  - QCD:
    - 30% due to uncertainty in misidentification rates estimated by varying selection criteria in control samples

$ZZ \to llll$: Results

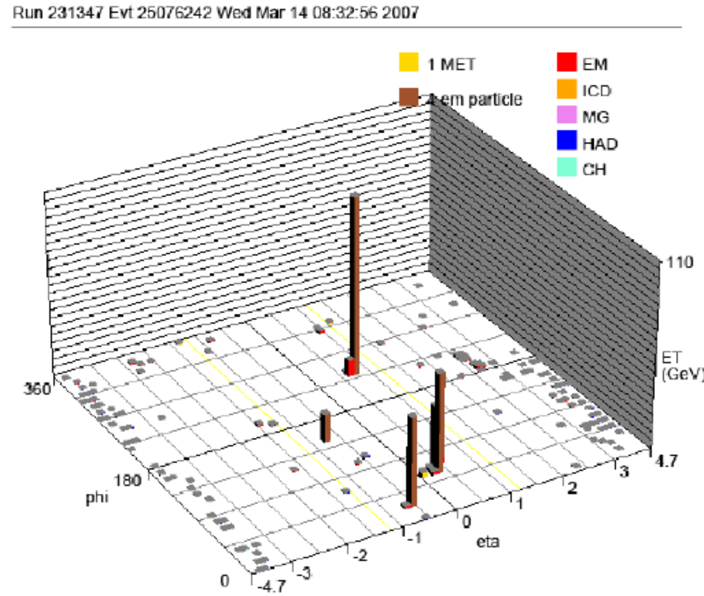
Subchannel	$4e_{2C}$	$4e_{3C}$	$4e_{4C}$	4μ	$2\mu 2e_{0C}$	$2\mu 2e_{1C}$	$2\mu 2e_{2C}$
Luminosity (fb^{-1})	1.75 ± 0.11	1.75 ± 0.11	1.75 ± 0.11	1.68 ± 0.10	1.68 ± 0.10	1.68 ± 0.10	1.68 ± 0.10
Signal	0.084 ± 0.008	0.173 ± 0.015	0.140 ± 0.012	0.534 ± 0.043	$0.058^{+0.007}_{-0.006}$	0.352 ± 0.040	$0.553^{+0.045}_{-0.044}$
$Z(\gamma)$+jets	$0.030^{+0.009}_{-0.008}$	$0.018^{+0.008}_{-0.007}$	$0.002^{+0.002}_{-0.001}$	0.0003 ± 0.0001	$0.03^{+0.02}_{-0.01}$	0.05 ± 0.01	$0.008^{+0.004}_{-0.003}$
$t\bar{t}$	–	–	–	–	$0.0012^{+0.0016}_{-0.0009}$	0.005 ± 0.002	$0.0007^{+0.0009}_{-0.0005}$
Observed events	0	0	$\boxed{2}$	$\boxed{1}$	0	0	0

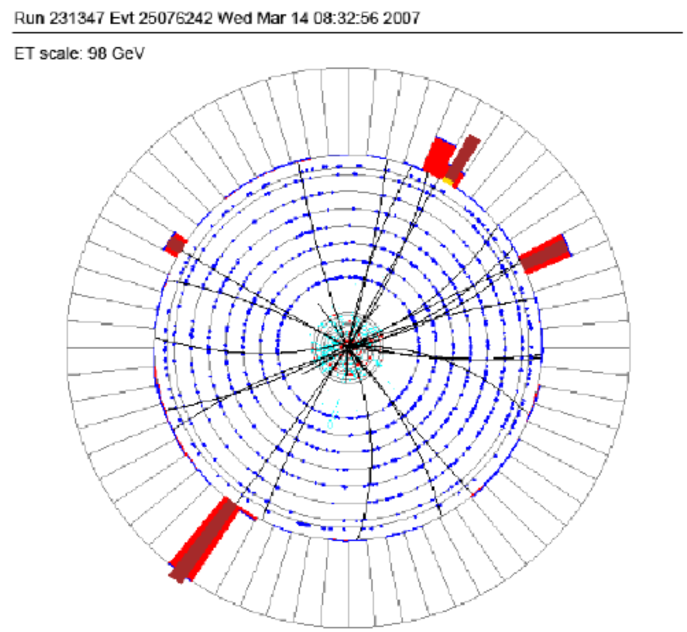




ZZ→*llll*: Candidate 1

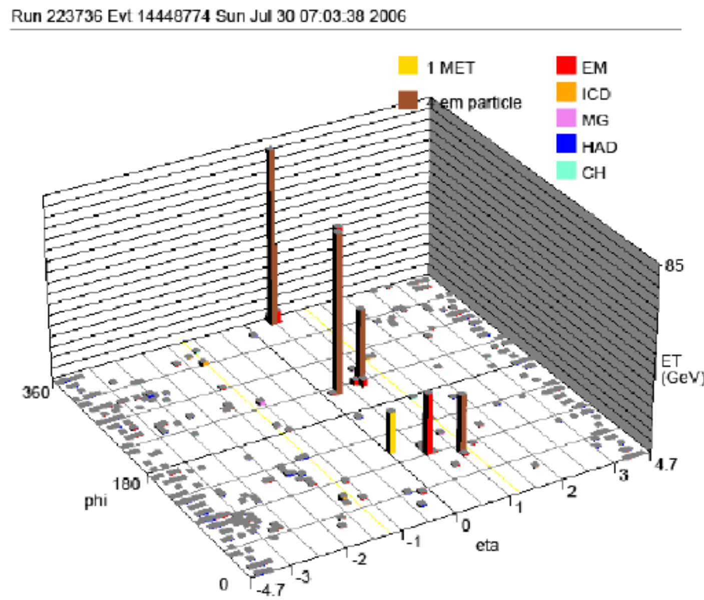
		e_1^+	e_2^+	e_3^-	e_4^-
4e candidate 1	p_T (GeV)	107	59	52	16
	η	0.66	0.25	-0.64	-0.85
	ϕ	4.10	1.08	0.46	2.62
	$M_{\ell\ell}$ (GeV)	$e_1^+e_4^-$ 89 ± 3		$e_2^+e_3^-$ 61 ± 2	

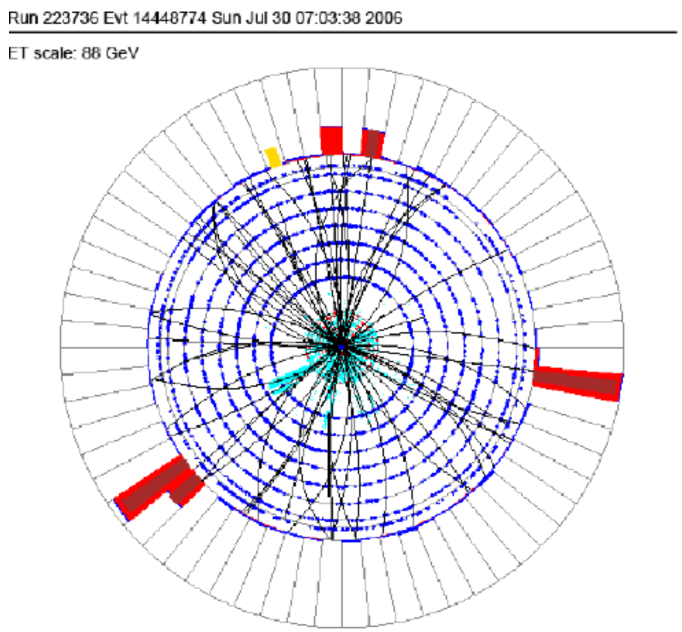




ZZ→*llll*: Candidate 2

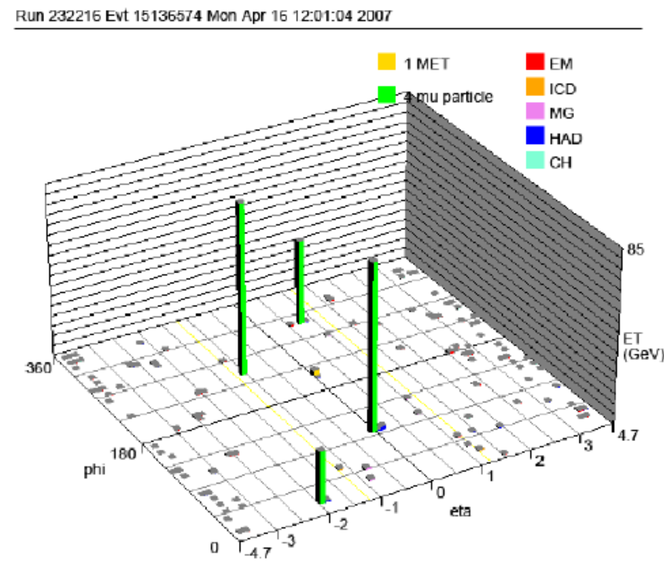
		e_1^+	e_2^+	e_3^-	e_4^-
4e candidate 2	p_T (GeV)	83	75	35	26
	η	0.64	0.40	0.85	1.17
	ϕ	6.16	3.80	3.83	1.40
	$M_{\ell\ell}$ (GeV)	$e_1^+e_3^-$ 99 ± 3		$e_2^+e_4^-$ 90 ± 4	

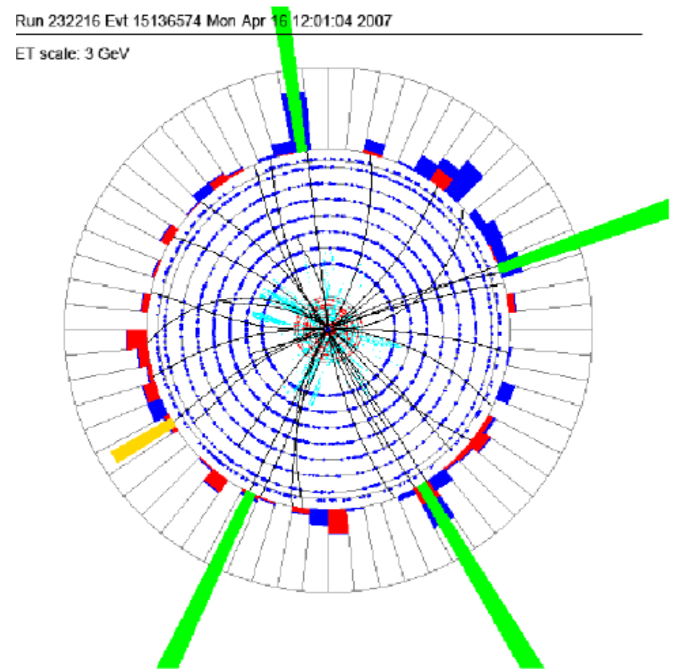




ZZ→*llll*: Candidate 3

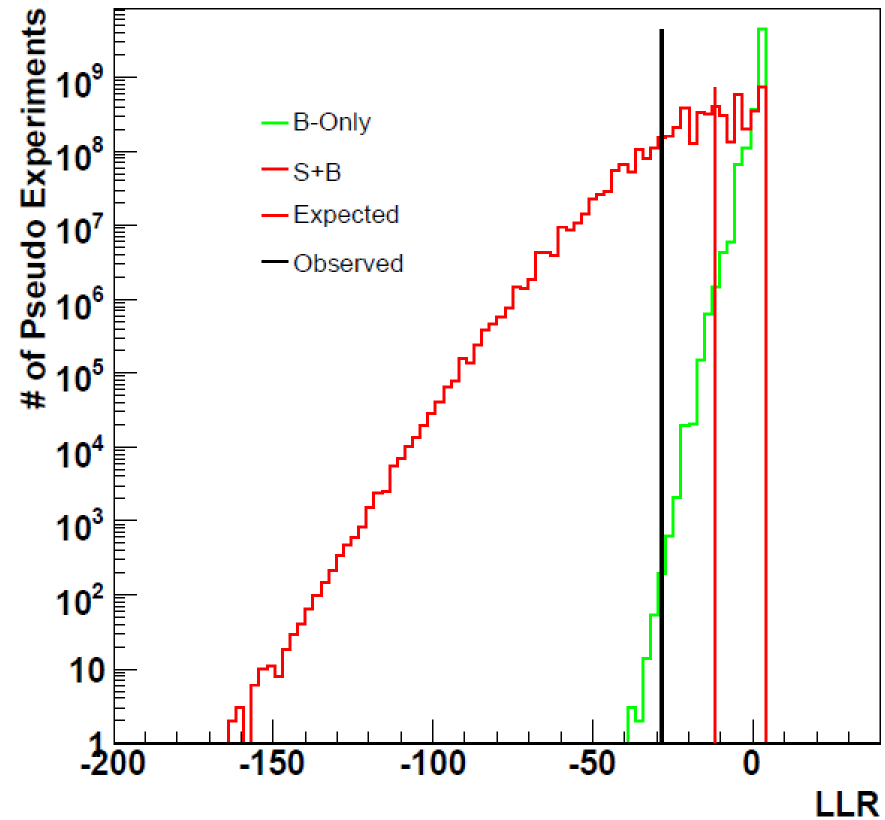
		μ_1^+	μ_2^-	μ_3^-	μ_4^+
4μ candidate	p_T (GeV)	115	77	42	24
	η	0.04	-1.01	0.77	-1.93
	ϕ	1.69	4.26	5.29	0.36
	$M_{\ell\ell}$ (GeV)	$\mu_1^+\mu_3^-$ 148^{+32}_{-18}		$\mu_2^-\mu_4^+$ 90^{+12}_{-8}	





ZZ→*llll*: Significance

- Use same LLR described previously
- Input is the yields (number of events) in each of the seven sub-channels
- In 5 x 10^9 pseudo-experiments, find 213 trials with an LLR value more signal like than that observed
  - Equates to a p-value of 4.3 x 10^{-8}
  - 5.3σ (3.7σ expected)



- Probability for signal plus background to give less signal-like observations than the observed one is 0.87

Combination

RunIIa 4*l* result

- For combination, need to scale signal and background expectation to new mass cut and we also lose the candidate event
  - Use MC samples from current analyses
  - Use mass and pT requirements from earlier analysis
  - Remove extra isolation requirements on muons
  - Repeat only changing the mass requirement to new values
  - Determine a scale factor applied expected signal and background from previous analysis and add the three channels into the LLR calculation

- A 3% systematic uncertainty is applied due to the rescaling

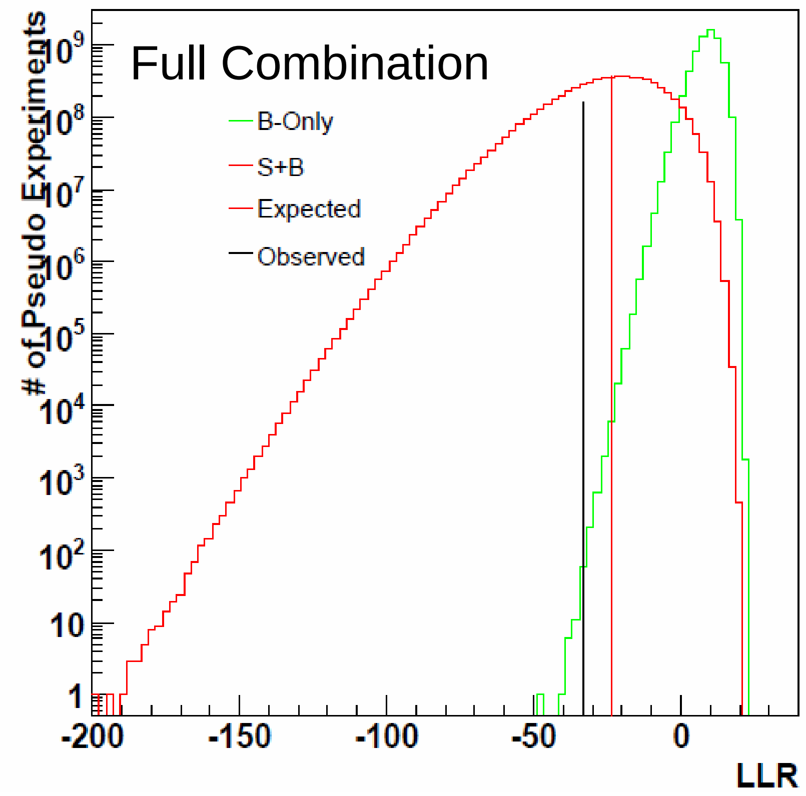
Shared Systematics

- Correlated
  - Lepton resolution
  - ZZ p_T spectrum
    - Account for higher order corrections on signal acceptance
  - PDF uncertainties

- Uncorrelated
  - Electron misidentification
    - Determined using different methods
  - Multihadron sample statistics
    - Regions of phase-space are different

Results

- Use same LLR test statistic
- Combination of the 4*l* analyses:
  - p-value of 2.9 x 10^{-7}
  - 5.0σ (4.2σ expected)
- Combination of above with 2*l*2ν analysis:
  - p-value of 6.2 x 10^{-9}
  - 5.7σ (4.8σ expected)



- Probability for signal plus background to give less signal-like observations than the observed one is 0.71

Results

- Minimize a fit to the systematic parameters in the LLR leaving the signal rate as a free parameter to extract the cross-section:

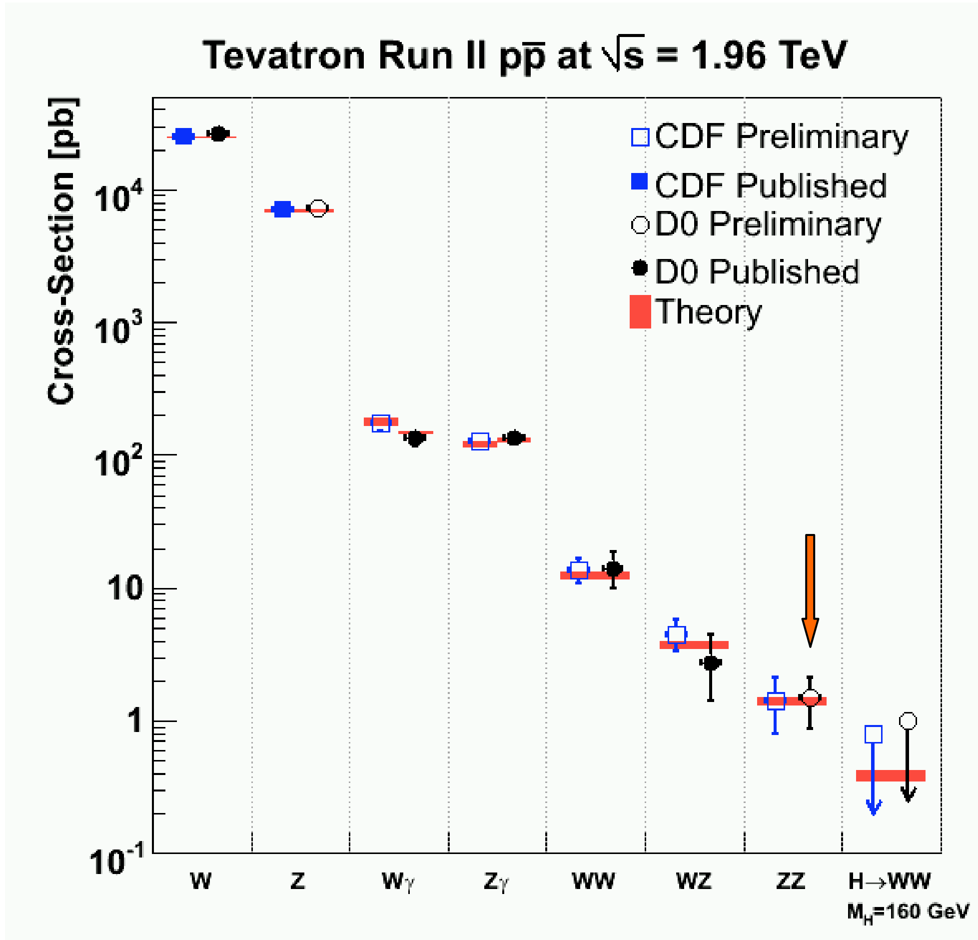
$$\sigma(ZZ) = 1.60 \pm 0.63\ (\mathrm{stat.})^{+0.16}_{-0.17}\ (\mathrm{syst.})\ \mathrm{pb}$$

- SM prediction: 1.4 ± 0.1 pb

- Accepted by PRL arXiv:0808.0703 [hep-ex] (2008)

Conclusions

- We look for ZZ using two channels: $2l2\nu$ and $4l$
- Combination of analyses results in an observation with significance of 5.7σ
- Cross section of combination is consistent with standard model expectation and in very good agreement with value measured by CDF
- More precise measurements of cross sections, study of kinematic distributions and limits on anomalous couplings as more data is accumulated



H→WW points not yet updated

Backup

Anomalous Couplings

- Excursions from the SM can be described via effective Lagrangian:

$$L_{WWV}/g_{WWV} = \boxed{g_V^1}(W^+_{\mu\nu}W^{\mu}V^{\nu} - W^+_{\mu}V_{\nu}W^{\mu\nu}) + \boxed{\kappa_V} W^+_{\mu}W_{\nu}V^{\mu\nu} + \frac{\boxed{\lambda_V}}{M_W^2} W^+_{\lambda\mu}W^{\mu}_{\nu}V^{\nu\lambda}$$

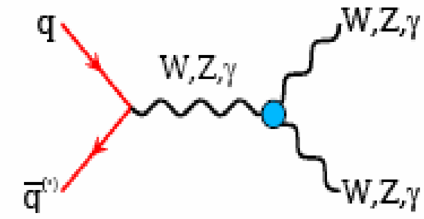
where $V = Z,\ \gamma$

In SM: $g_V^1 = \kappa_V = 1, \quad \lambda_V = 0$

$(\Delta\kappa = \kappa - 1) \quad (\Delta g^1 = g^1 - 1)$

- Cross section increases especially for High E_T bosons ($W/Z/\gamma$).
- Unitarity Violation avoided by introducing a form-factor scale Λ, modifying the anomalous coupling at high energy:

$$\lambda(\hat{s}) = \frac{\lambda}{(1+\hat{s}/\Lambda^2)^n}$$ (Not an issue at LEP)



$q\bar{q}' \rightarrow W^{(*)} \rightarrow W\gamma$: $WW\gamma$ only

$q\bar{q}' \rightarrow W^{(*)} \rightarrow WZ$: WWZ only

$q\bar{q} \rightarrow Z/\gamma^{(*)} \rightarrow WW$: $WW\gamma, WWZ$

$q\bar{q} \rightarrow Z/\gamma^{(*)} \rightarrow Z\gamma$: $\boxed{ZZ\gamma, Z\gamma\gamma}$

$q\bar{q} \rightarrow Z/\gamma^{(*)} \rightarrow ZZ$: $\boxed{ZZ\gamma, ZZZ}$

Absent in SM

Two types of effective Lagrangians with:

on-shell Zγ (ZγZ*,Zγγ*)		on-shell ZZ (ZZZ*,ZZγ*)
h_{10}^V, h_{20}^V	(CP violating)	f_{40}^V
h_{30}^V, h_{40}^V	(CP conserving)	f_{50}^V

SM predicts all to be 0

Limits on anomalous ZZZ^* and $ZZ\gamma^*$ couplings

- ZZ channel sensitive to two couplings
- 95% CL limits on anomalous couplings for Λ = 1.2 TeV

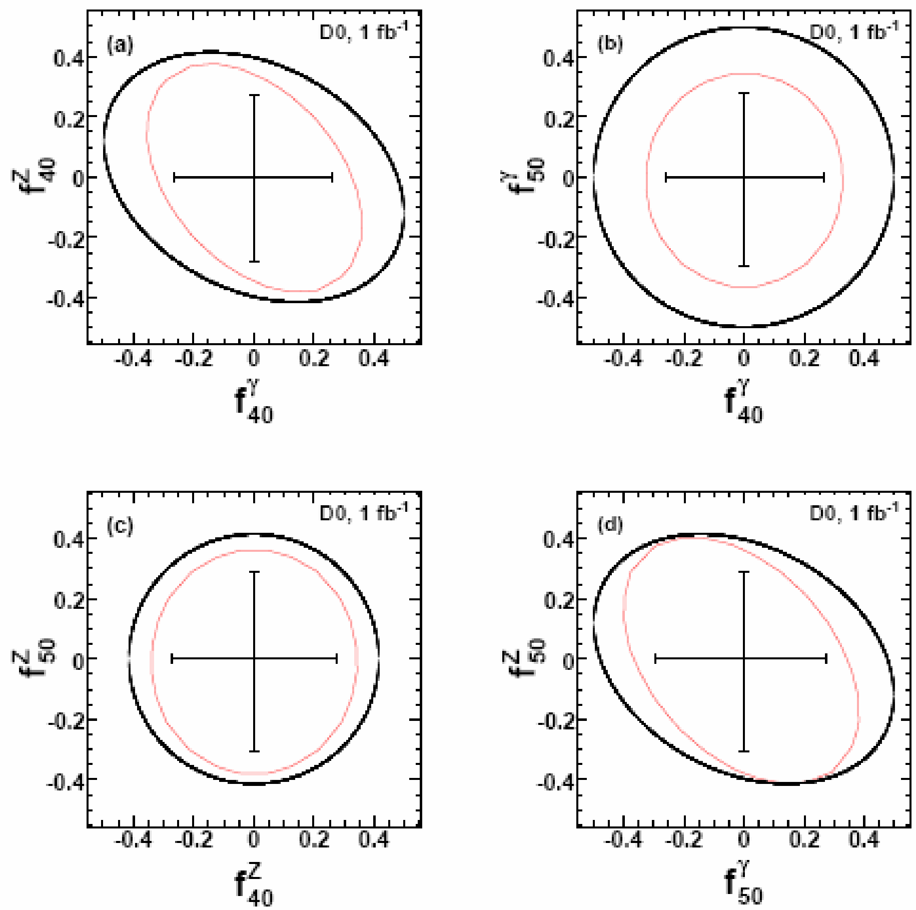
$$-0.28 < f_{40}^{Z} < 0.28$$

$$-0.31 < f_{50}^{Z} < 0.29$$

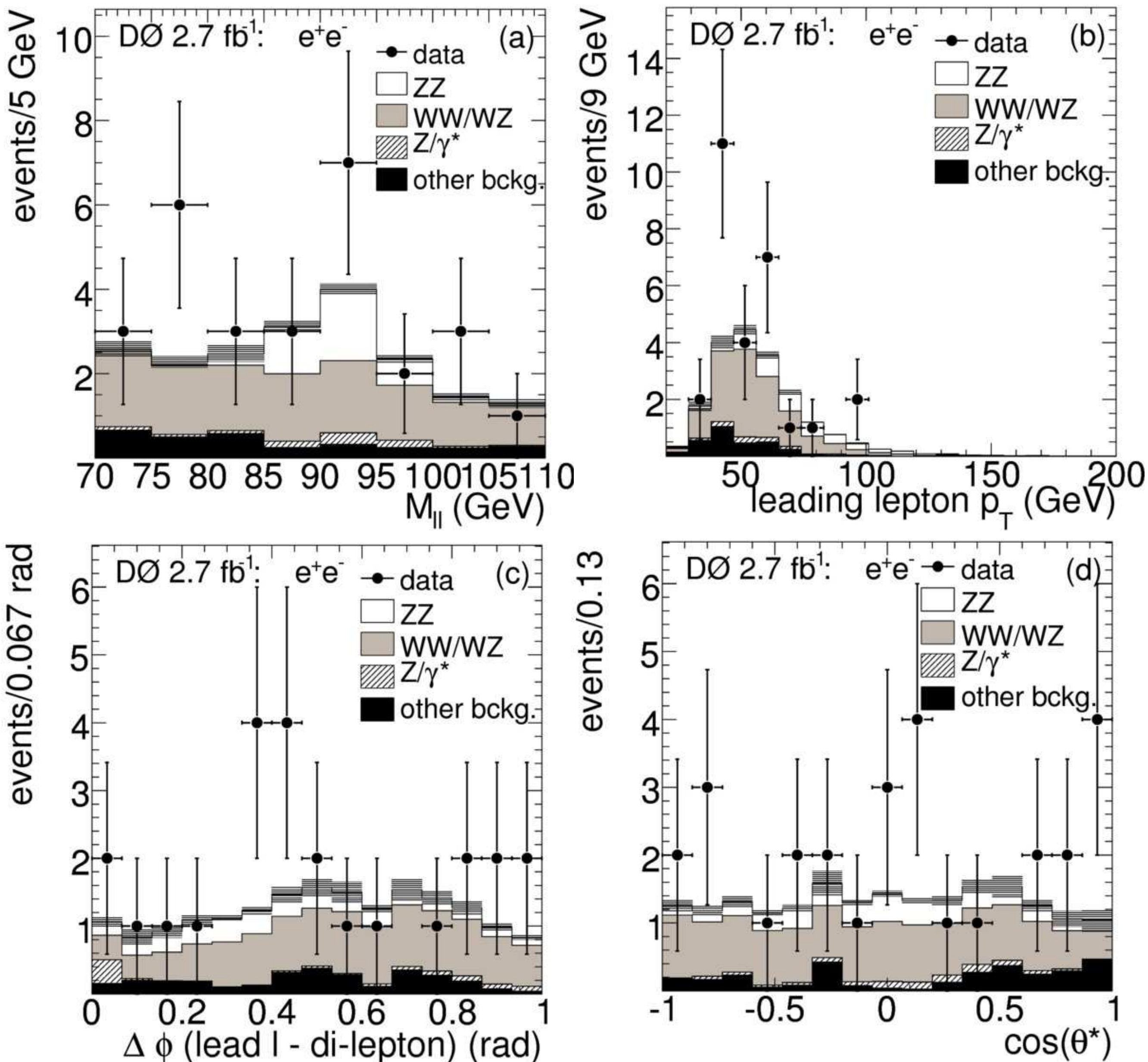
$$-0.26 < f_{40}^{\gamma} < 0.26$$

$$-0.30 < f_{50}^{\gamma} < 0.28$$

- First bounds on these limits from Tevatron
- f_{40}^{Z}, f_{50}^{Z}, f_{50}^{γ} are most restrictive to date



ZZ→$ll\nu\nu$: Dielectron likelihood Inputs



ZZ→$ll\nu\nu$: Dimuon likelihood Inputs